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Modelling deep decarbonization of industrial energy consumption under 2-degree target: Comparing China, India and Western Europe

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HIGHLIGHTS:

- Industry sector could be greatly impacted by socio-economic development.
- At least 118 Gt of CO2 mitigation is required for 2-degree target from 2010 to 2050.
- Energy intensity of different regions would rapidly converge under 2-degree target.
- Electrification is a critical measure for industry sector's deep decarbonization.

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ABSTRACT

The decarbonization of industrial energy consumption is critical for global climate change mitigation, and this process can bring multiple challenges, especially for regions at the early stage of industrialization. To explore the possible transitions of industry sector under 2-degree target, this paper applied a 14-region energy system model (Global TIMES) to analyze the transition pathways of industry sector. The socio-economic uncertainty was considered by introducing Shared Socio-economic Pathways into scenario design. Moreover, a comparison between China, India and West Europe was conducted, to provide information on the key challenges for regions at different industrialization stages. Modeling results show that: 1. In reference scenarios, global industrial energy demand and CO2 emissions would keep growing in next decades, industry sector may emit over 25% of total energy-related CO2 emissions in 2050; 2. The changes in socio-economic developing pattern could slow down the emission growth, however, under 2-degree target, at least 118 Gt of additional emission reduction is required from 2010 to 2050; 3. The mitigation requirement would lead to great energy structure changes including rapid electrification, electricity may be able to provide nearly 40% of Western Europe's industrial final energy consumption by 2050; 4. Improvement on energy intensity would be accelerated in RCP26 scenarios, especially for emerging economies, by mid-century, China and India's industrial energy intensity would reduce by over 60% and 50% respectively, compared with 2010's level.

1. Introduction

CO2 emission reduction from industrial energy consumption plays a vital role in global climate mitigation. In the last decades, final energy consumption of global industry sector kept growing and reached 115 EJ by 2016, and over 60% of the energy supply came from fossil fuels [1]. Therefore, industrial energy consumption could lead to a large amount of CO2 emissions, in 2016, industry sector emitted 23.8% of the global CO2 from fuel combustion [2]. In future, industry sector is expected to get further expansion as the economy develops, especially in developing countries. The CO2 mitigation in industry sector could become a critical task to realize global climate targets.

It is worth noticing that the CO2 mitigation processes of industry sector could have significant differences between regions, especially when they are at different industrialization stages. Take the contrast between China and India as an example, although they are both developing countries with a similar population, their industrial energy demand varied a lot. In 2016, India's final energy consumption in industry sector is less than 1/5 of China's [1], an important explanation is that these two countries are at different stages of industrialization, according to the descriptions in Chenery's studies [3–5]. In the last three decades, China has made great effort on promoting industrialization, lots of heavy industries experienced fast expansion, and some of them may reach the saturation in the near future [6–9]. Thusly,

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technology intensive industries are expected to have bigger share in the whole industry sector, which could lead to lower energy intensity [10]. While there is another situation in India, India only produced 96 Mt of crude steel in 2016, and its steel demand is expected to double within ten years with the infrastructure development [11]. Further expansion of heavy industries including steel and cement would continue in India. Therefore, the industrial energy demand of these two regions is different at present and in the coming years, even if they have close population and economic growth rate.

Given the increasing CO2 emissions in industry sector, several researches have been conducted to explore its mitigation options and strategies. From the perspective of research scope, many of the researches have put the focus on one particular industry or a single region, analysis for the whole industry sector is relatively lacking. Besides, most existing studies haven't taken enough consideration on regional differences or economic uncertainties, while the energy demand of industry sector can be greatly influenced by socio-economic development and also regional industrialization process.

One of the most popular topics is the strategy on improving energy efficiency and carbon intensity of a particular industry, and energy-intensive industries attracted lots of attention. Sharma et al. proposed a mitigation option for India's paper industry – applying solar industrial process heating, the CO2 mitigation potential of this measure is estimated to be 0.34 Mt [12]. An et al. estimated the energy saving and CO2 mitigation potential for China's steel industry and pointed out the importance of promoting low-carbon technologies [13]; Buhler et al. analyzed the possible energy savings in the German chemical industry, proposed the cost curve for energy efficiency measures [14]; Saidur et al. focused on the Malaysian rubber producing industry, concluded that significant energy savings could be realized in the existing equipment [15]; Rooij et al. evaluated the CO2 mitigation potential of a plasma process for the chemical industry, this process is proven to be more cost-effective than energy efficiency measure in this study [16]. In addition to these papers, there are many similar studies [17–22] providing important information for a specific industry's roadmap making. However, further exploration to get insights on how energy consumption of the whole industry sector could react under climate target are still required.

Knowledge sharing and cooperation between regions are critical to tackling global warming [23], while few studies presented the comparison for different countries' industrial energy transitions under a shared climate target. Most existing studies related to industry sector mitigation only involved one independent region, among which, developed regions and emerging economies are the most concerned, few researches choose a more macro perspective. Kajaste et al. published a paper covering major regions including China, India, Europe, America, etc. However, the main focus of this paper is not to present the regional differences in industry sector, instead, it compared the potential and cost of different measures for cement industry, and stated that CCS could be a cost-effective mitigation measure in long-term [24].

This research aims to provide insights on how global industry sector should transform under 2-degree target and also to explore the key energy transition challenges for countries at different stages of industrialization. To generate results on energy demand and related CO2 emissions for global industry sector, a 14-region global energy system model is used. China, India and Western Europe are chosen as examples for regional comparison, since they can be considered to be at different stages of industrialization [4].

In Section 2, the methodology used in this research will be introduced briefly, including basic information of Global TIMES model. Section 3 presents the main results, where the industrial energy-related CO2 emission pathways and required energy transitions will be analyzed. Section 4 concludes the key points and also provides some discussions on further research.

2. Methodology

2.1. Global TIMES model

Integrated assessment models (IAMs) are established tools to study climate mitigation by combining physical and economic analyses. After decades of effort, several global IAMs have been developed and successfully applied to support energy and climate policies. Among these models, certain differences exist in the construction of energy systems. For REMIND [25], WITCH [26] and GEM-E3 [27], computable general equilibrium modelling has been conducted for the whole economy, and energy system is constructed as one of the economic sectors. In this case, the technical details in energy system may be lacking. For GCAM [28], MESSAGE [29] and IMAGE [30], independent energy system have been built with technical details, while the economy module has been simplified. The linkage between energy system and macro economy are described by introducing major indicators including GDP. Since scenario analyses for climate mitigation usually involve long timescale, huge uncertainty would arise, it is of great value to conduct studies with different models.

The Integrated MARKAL-EFOM System (TIMES) is an energy system model generator developed by IEA's Energy Technology Systems Analysis Program. TIMES model aims to supply energy services at a minimum global cost, and the solving theory including objective function, equations and decision variables are explained in the documentations [31]. Compared with other models, one major advantage of TIMES model is that it can provide lots of technical details and represent energy flow dynamics over multiple periods. For example, the hourly changes of the electricity load can be described in a TIMES model, which make it possible to consider the volatility of the real power system. Besides, since TIMES model adopts the linear programming method to solve complex problems efficiently, it is widely used in energy system modelling under climate mitigation [32–37].

Global TIMES model is a multiple-region energy system model covering 2010 – 2050, in which the whole world is divided into 14 regions. Based on the modelling experience of a single region model China TIMES [38–46], Global TIMES model is also developed by Tsinghua University [47–52]. To describe the complete energy flow including extraction, conversion, transmission and consumption, six sectors have been constructed for this model: upstream, power, agriculture, building [50,51], industry [52] and transport. Model runs are driven by the projected energy service demand of four end-use sectors. Also, with specific parameters and equations, energy policies or climate targets can be introduced in scenarios to analyze their impacts on energy system. However, it is worth mentioning that energy system transitions' feedbacks on the economy have not been well presented in Global TIMES model, as the model run only reaches partial equilibrium within energy system.

To design the reference energy system is the foundation of Global TIMES model construction. Upstream sector is described as a primary energy supply department, energy production and transformation processes including fuel extraction, oil refinery have been considered. A technology-rich power sector is built in Global TIMES model, in addition to traditional power generation technologies including thermal power and hydropower technology, multiple new power sources have also been considered: solar PV, onshore wind, offshore wind, nuclear, geothermal, ocean, and so forth. For end-use sectors, technology databases are constructed according to their energy service demands, a total of over 400 of technologies have been described in end-use sectors considering the differences in technical types and advancement. With the consideration of abundant technologies and energy sources, technology competition within a sector is allowed.

To construct the reference energy system on the model platform, the linkage betweentechnologies and commodities should be clarified with the introduction of different parameters. Table 1 provides an example of required parameters for industrial technologies. To decide the

Table 1
Parameters required for steam boiler in steel production.

Technical parameter		Economic parameter	
TOP-IN	Input commodities	NCAP-COST	Investment cost
TOP-OUT	Output commodities	NCAP-FOM	Fixed operation cost
ACT-EFF	Technology efficiency	ACT-COST	Variable costs
FLO-EMIS	Emission factor	NCAP-TLIFE	Technical lifetime
NCAP-AF	Operating hours	—	

techno-economic parameters for these technologies, several databases and publications have been used as reference [53–57]. Although these databases and publications made great efforts on energy technologies projection, the uncertain technical progress will still cause big uncertainty for the scenario analyses.

As an independent end-use sector, industry sector's energy service demand is projected based on historical data of each region and assumptions on future socio-economic development. Global TIMES model considered several energy-intensive industries including steel industry, paper industry, chemical industry, non-mental industry and non-ferrous industry; in current model version, other industries are simplified as one category; and also, the feedstock demand including coal, oil and gas has also been considered as non-energy use. The simplified energy flow of industry sector is shown as Fig. 1. For each industry, several energy services including process heat, machine drive, electrical chemistry and others have been considered. Besides, in order to better describe end-use sector's reaction under emission constraint, elastic demand function was introduced for industry sector, which allows the model to reduce the energy service demand as system cost gets higher under stringent emission constraints.

As mentioned above, the whole world has been divided into 14 regions according to the geographical location and the socio-economic conditions in Global TIMES. In this research, a regional comparison will be conducted between China, India and Western Europe.

2.2. Key assumptions and scenarios

Several assumptions have been made to conduct scenario analyses with Global TIMES model, as shown in Table 2.

To project the energy service demand for model input, a driver-elasticity method is applied for each end-use sector [59]. The driver refers to the socio-economic indicator which brings significant changes to the specific energy service demand. Based on the existing publications [61–65] and socio-economic database [66] of Shared Socio-economic Pathways, major socio-economic indicators including household numbers can be used or estimated in this research. After the driver is decided, each energy service demand will be linked to the driver by a constant number – elasticity, which reflects the socio-economic growth's influences on energy service demand.

This paper designed two groups of scenario to explore industry sector's emission pathways: the reference scenario group with no specific constraints on CO2 mitigation, and the 2-degree scenario group with global CO2 budget constraint.

Five reference scenarios have been proposed based on typical socio-economic trajectories SSP1-SSP5, to show how energy system and mitigation pathway of industry sector can be influenced by socio-economic development. Each trajectory describes a possible future with unique definition, SSP1 - SSP5 are named in turn as Sustainability, Middle of the Road, Regional Rivalry, Inequality, Fossil-fueled Development, the detailed descriptions are provided in former studies [58]. Among all the trajectories, SSP2 is thought to be a mild trajectory without major and drastic changes from the historical trend, therefore it can be used as the benchmark for the comparing analyses.

Although this paper focuses mainly on the industry sector, the model optimization is conducted for the whole energy system. With the introduction of emission constraint, energy system transitions of all the regions would happen under a uniform carbon price endogenously generated by the scenario runs, which indicates the mitigation pathway of 2-degree scenario is expected to be global cost-effective.

2.3. CO2 emission decomposition

This paper has identified four important factors that may bring great influences on industrial energy-related CO2 emissions: economic development, industrial structure, energy intensity and carbon intensity. To evaluate the contribution of each factor, a decomposition method Log Mean Divisia Index is introduced.

Kaya identity is a useful tool to analyze the level of human impacts on Climate [67], this research has made minor changes for the original kaya equation, and divided the industrial CO2 emissions as the production of four parts, as shown in Eq. (1). GDP reflects the development of macro economy; the quotient of industrial value-added and GDP stands for the industrial structure which reflects industry sector's importance in the economy; the quotient of final energy and value-added industrial stands for energy intensity which reflects the energy intensity in industrial production; the quotient of CO2 and final energy stands for carbon intensity of industrial energy consumption.

$$CO2 = GDP \cdot \frac{Industrial\ \ value\ \ added}{GDP} \cdot \frac{Final\ \ energy}{Industrial\ \ value\ \ added} \cdot \frac{CO2}{Final\ \ energy} \quad (1)$$

Log Mean Divisia Index (LMDI) method [68,69] has been used to calculated the contribution of each factor in industrial energy-related CO2 emission, the calculation base year is chosen to be 2010.

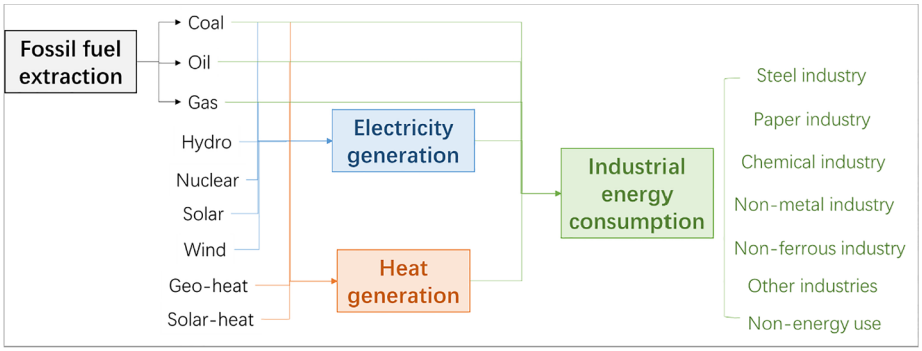

Fig. 1. Simplified energy flow in industry sector.

Table 2
Major assumptions.

Model related	Energy service demand	Shared Socio-economic Pathways [58] Driver-elasticity method [59]
	Resource potential	Resource curves for each region [47]
Scenario related	2-degree target	Carbon budget for 2010–2050: 1095 Gt [60]
	Technology	Exogenous technological progress
	Carbon price	Endogenous uniform price for all regions

3. Results

3.1. Energy-related CO2 emissions in industry sector

3.1.1. Global CO2 emission pathway

In reference scenarios, energy-related CO2 emission from global industry sector is expected to grow in the coming decades and reach 11–17 Gt in 2050. CO2 emission in industry sector may experience faster growth than in other sectors, in 2015, industry sector accounts for 21.3% of the total energy-related CO2 emission, and this share would gradually increase to 25% by mid-century. It is indicated that industry sector will always be an important part for global carbon mitigation.

Although all scenarios show an increasing emission trend, differences in socio-economic developing assumptions could bring great impacts on industrial CO2 emissions. Comparing the five reference scenarios, the gap in CO2 emission would occur since 2025 and gradually widen to 5.2 Gt by 2050, as shown in Fig. 2. Take SSP5 trajectory as an instance, it represents a future where rapid economic development will be sustained with high-speed technological progress, therefore global industry sector will also experience great expansion. Moreover, SSP5 has a strong dependency on fossil fuels, which will lead to a carbon-intensive energy system. Consequently, in SSP5 scenario, the industrial CO2 emissions could reach 17.4 Gt by 2050, 29–46% higher than other scenarios.

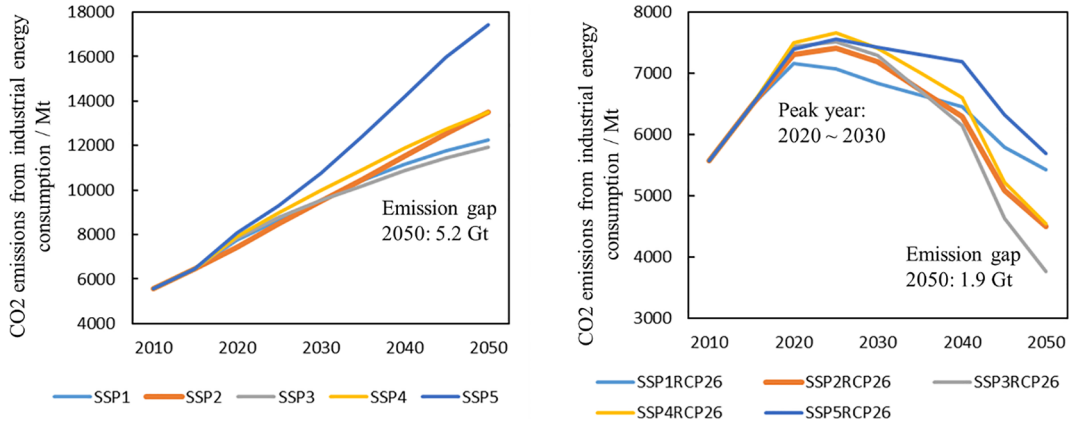

Fig. 2. Global CO2 emissions from industrial energy consumption (left: reference scenarios, right: RCP26 scenarios).

The improvements on socio-economic development pattern are not sufficient to meet the required emission reduction of 2-degree target, specific measures on CO2 mitigation are required. The emission space for 2-degree scenarios is very limited, therefore, the emission pathways of different scenarios would gradually converge, and by 2050, the gap could be narrowed down to 1.9 Gt. To achieve 2-degree target, huge emission reductions would be required from reference scenarios, no matter which socio-economic trajectory is to be chosen. SSP1 is the sustainable trajectory, and benefiting from its effort on energy conservation and low-carbon development, the industrial CO2 emission growth could be slowed down. As a result, the mitigation challenge for SSP1 trajectory under 2-degree target can be also partly eased. Even so, CO2 mitigation of 2.7 Gt and 6.8 Gt would be required from SSP1 scenario in 2030 and 2050.

From a global perspective, CO2 emission from industrial energy consumption is required to peak at around 2020 and then begin to decrease in RCP26 scenarios. To meet the carbon budget, industry sector should contribute 118–173 Gt of cumulative emission reduction during the modelling period. While the mitigation process in different regions may vary greatly, especially when they are at different stages of industrialization. In this research, we took India, China and West Europe as the representatives of early, late and post-industrial regions respectively.

3.1.2. CO2 emission pathways of India, China and West Europe

Among these three regions, only India is expected to experience sustained rapid growth in industrial energy-related CO2 emissions. Currently, the service sector is the largest sector in India, as 54% of the GDP comes from it in 2016, and the share of industry sector is only 29% [70]. However, the improvement on infrastructure would be necessary for both the economic development and live quality promotion, and a large amount of new demand on industry products may arise, bringing significant growth for industry sector. In all reference scenarios, the CO2 emission from industrial energy consumption will increase sharply, by 2050, India may account for 17–25% of the global total. And in SSP5 scenario, India may even overtake China to become the biggest emitter by 2050.

With more than 30 years' efforts, China has entered a late stage of industrialization [71], the CO2 emissions will increase at much slower speed and may even begin to decrease in next decades. On the one hand, improvements on industrial structure would occur, traditional energy-intensive industries are expected to enter saturation in near future, and the expansion of high-tech industries may gradually become the major growth point. On the other hand, the Chinese government has implemented a series of policies to increase the energy efficiency in industry sector. It is foreseeable that the historical growing trend in CO2 emissions would slow down in the coming years. And for trajectories with specific emphasis on environment protection or technology progress such as SSP1 and SSP5, CO2 emissions in industry sector may even reach the peak before 2020.

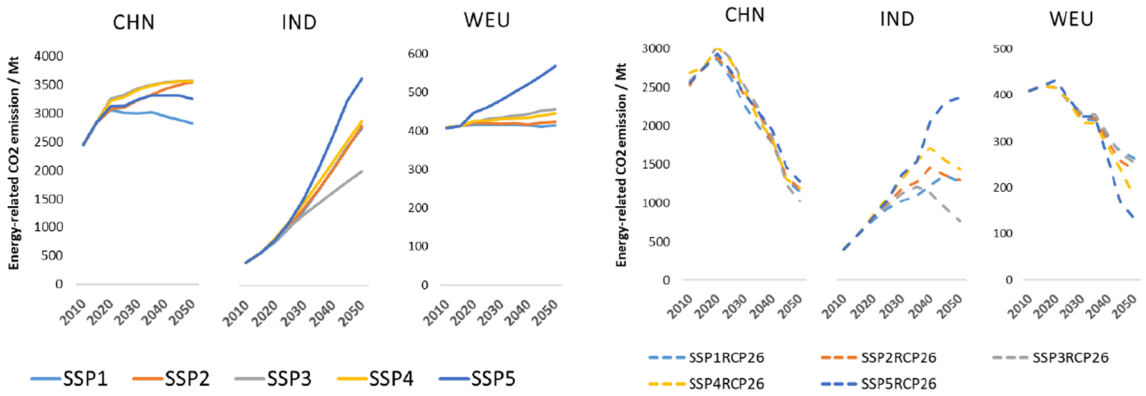

Fig. 3. CO2 emission pathways of major regions (left: reference scenarios, right: RCP26 scenarios).

For Western Europe, there may not be many major changes from the current situation, unless the fossil-fueled development trajectory SSP5 will be followed. Most of the countries in Western Europe has already built a steady industrial system, therefore the CO2 emission from industrial energy consumption wouldn't change much in most reference scenarios. Only when the society is shifting toward SSP5 trajectory, a further increase might occur.

When 2-degree target is introduced to the global energy system, most regions are required to reduce the industrial CO2 emissions by a large amount.

Developed regions including Western Europe needs to begin the absolute mitigation in industry sector as soon as possible. As shown in Fig. 3, rapid decrease in emission would occur since 2020, and by 2050, CO2 emissions from industrial energy consumption could decrease to 250 – 112 Mt, which is 40 – 70% lower than its 2015's level. Based on the cost-optimal modelling results, a total of 2.5–6.6 Gt of CO2 mitigation would be achieved by Western Europe from 2010 to 2050.

For China, industrial CO2 emissions may be able to have limited growth in the near future, and emission peak is expected to occur between 2020 and 2025. The emission peak value of industry sector would be around 2.9–3.3 Gt, 4–18% higher than current level. During 2010–2050, China's industry sector may be able to contribute 14–37 Gt of CO2 cumulative mitigation.

India would be one of the late-peaking regions, and its emission pathways vary a lot under five mitigation scenarios. Since India is going to have rapid development in next decades, the different socio-economic assumptions could bring great influence on its mitigation process. Regional Rivalry trajectory SSP3 would reach the emission peak at the earliest, in which scenario India's development may be affected by inter-regional barriers on trade and technology. In SSP5 scenario, rapid economic growth would drive the industrial CO2 emission to keep increasing until 2050. The potential mitigation contribution of India would be around 12–18 Gt.

In summary, all regions need to make great effort in industry sector's mitigation to achieve global climate target. Developed regions like Western Europe should promote absolute mitigation from now on, for developing regions such as China and India, limited growth space may be possible in the near future, while absolute mitigation would still be necessary before 2050 in most scenarios.

3.2. CO2 emissions decomposition

To identify the most influential factors for industrial energy-related CO2 emissions, LMDI method is introduced to calculate the contributions of GDP, economic structure, energy intensity of industrial production and carbon intensity of energy consumption. The main results are shown in Fig. 4.

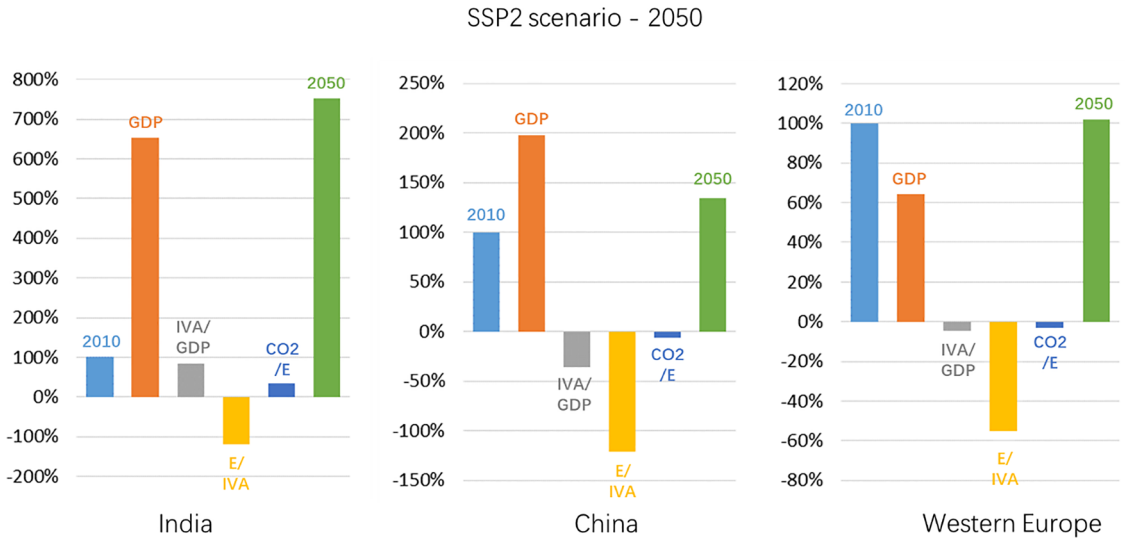

Fig. 4. CO2 emissions decomposition results in 2050.

GDP growth is the biggest driving force for CO2 emissions, especially in developing regions. In reference scenarios, global GDP growth would bring 5.1–6.9 Gt and 8.1–16.9 Gt of CO2 emission increase for industry sector in 2030 and 2050.

The economic structure change could be one of the biggest

differences for regions in different stages of industrialization. For post-industrial regions including West Europe, a stable economic structure has been already constructed, therefore the indicator IVA/GDP may not bring significant impacts in CO2 emission. Since more non energy-intensive industries are expanding, the coming economic structure change in China could cause falling in industrial CO2 emission, resulting in around 1 Gt of emission reduction in 2050. On the contrary, India is expected to have a higher share of energy-intensive industries in next decades, the economic structure change could become a driving force in the CO2 emission growth in industry sector, and cause 300 Mt of additional CO2 emission.

In reference scenarios, energy intensity reduction would be the most important measure to reduce CO2 emissions. This reduction could come from two aspects, one is the expansion of technology-intensive industries with high added-value, the other is the improvement of energy efficiency. For developing regions including China and India, energy intensity improvement would be especially effective. In SSP1 scenario, China's energy intensity improvement is expected to cause over 2000 Mt of CO2 emission reduction by 2050. For developed regions like West Europe, since they have already built a high added-value industry and applied high-efficiency technologies, further improvements could be quite limited.

3.3. Energy transitions in industry sector

Generally, final energy consumption of industry sector would increase as the economy grows. However, to meet the mitigation requirements of 2-degree target, advanced and clean technologies need to be deployed in large-scale, bringing the effects on both the final energy demand reduction and fuel structure improvement.

3.3.1. Energy intensity improvement

With the industry upgrading and technology progress, the average energy consumption of unit industrial value-added will hopefully reduce by 40% in 2050, compared with 2010's level.

Among the different socio-economic development patterns, both sustainable transition and technical progress can accelerate the energy intensity reduction. As shown in Fig. 5, SSP1 and SSP5 are expected to get the lowest energy intensity by mid-century, although they are heading to vastly different futures. In SSP1 scenario, with targeted measures on sustainable development, the energy consumption per unit added-value will decrease by 37% and 42% in 2030 and 2050. SSP5 focuses more on the development and promotion of advanced technology, which can result in an energy intensity reduction of 39% in 2050, compared with 2010's level.

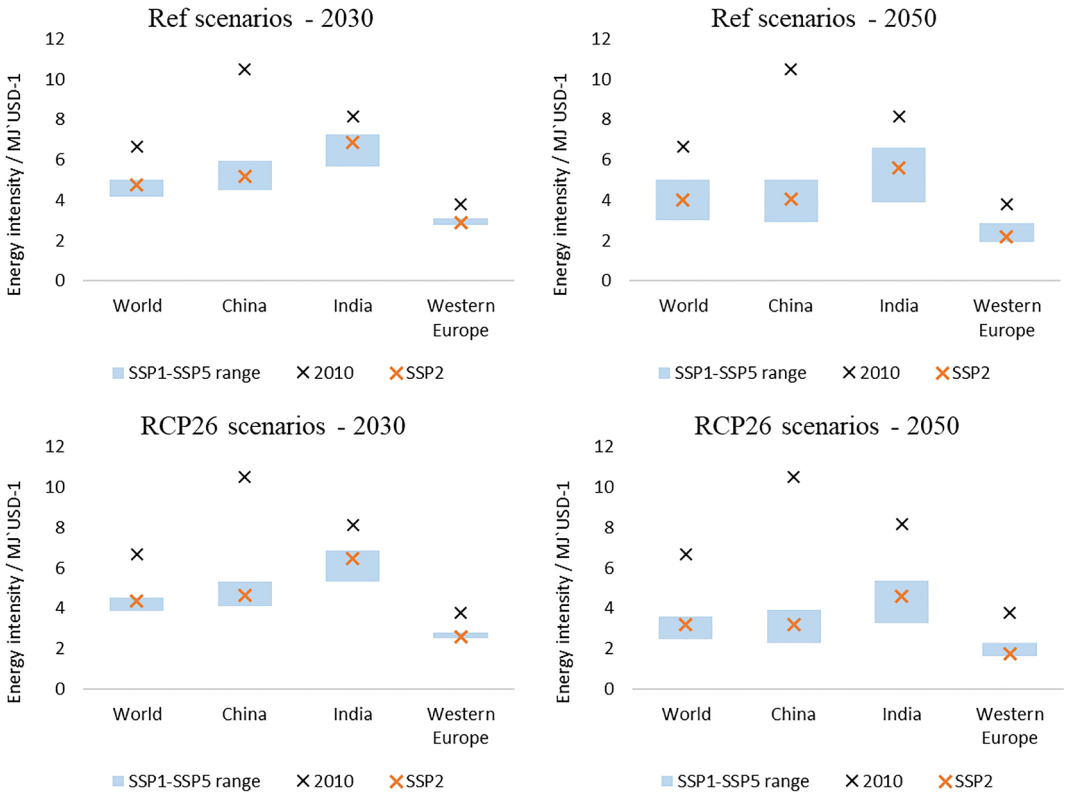

Fig. 5. Energy consumption per industrial value-added.

Initiative energy structure improvement will be rather slow for the cost advantages of fossil fuels, while stringent emission constraint could drive rapid transitions. In reference scenarios, most regions' fuel mix in industry sector will only experience minor changes in the coming years, therefore its impact on industrial CO2 emission is also limited. Under RCP2.6 carbon constraint, significant improvement in industrial energy structure would become essential both in worldwide and for every single region. Take China for instance, energy structure transition could bring 1.5 Gt of emission reduction in SSP3RCP26 scenario by 2050, which accounts for 40% of the total reduction.

To tackle climate change, further improvement on industrial energy intensity are essential in all trajectories, and the gap between different regions should be narrowed down rapidly. In 2010, China's industrial energy intensity was around 2.8 times of Western Europe's level. This gap will gradually reduce under the mitigation task, in SSP5RCP26 scenario, this indicator in China is only 44% higher than in West Europe by 2050.

Western Europe's current energy intensity is much lower than the world average, to further reduce its industrial energy consumption, the reduction of industrial product demand may become one of the key

measures. From 2010 to 2050, 40–58% of energy intensity reduction would be required in RCP26 scenarios. Since Western Europe has already applied advanced technologies in industry sector, further improvement in energy efficiency could be challenging and expensive. While the model results show the industrial energy service demand in Western Europe should reduce by nearly 20% in RCP26 scenarios by mid-century, which indicates reducing industrial products consumption is becoming critical. More explorations on promoting circular economy including products recycling should be conducted in the coming years.

China may get the most rapid reduction in the next decades, a significant improvement in energy efficiency is necessary for industry sector. In RCP26 scenarios, the energy intensity in China's industry sector is required to decrease to 2.3–3.9 MJ/SUD in 2050, 63–73% lower than 2010's level. Current policies on backward capacities elimination and industrial structure improvement are not sufficient to achieve the required reduction. Based on model results, all the new projects should be equipped with the best-available technologies, which would need the promotion of more strict standards on minimal energy efficiency. Moreover, in China, since there are a considerable number of small and medium-sized industrial enterprises, the strengthened supervisions are also necessary to ensure the energy intensity target could cover them.

For new emerging economies such as India, great uncertainties would exist in its energy intensity improvement because future development patterns can vary a lot. Since India is at the early stage of industrialization, the communication and cooperation between regions could bring great impacts on its technological progress. Therefore, although every single RCP26 scenario would experience intensity reduction in future, the gap between them can be large. Take SSP3 as an instance, for the lack of regional cooperation, access to advanced technology could always be difficult and expensive in India, and the energy intensity in SSP3RCP26 scenario could be 69% higher than SSP1RCP26 scenario in 2050.

Climate mitigation is a global-shared mission, and if the communication on technical progress could be fully shared across regions, developing regions may be able to construct their industry sector with low energy intensity at less expense.

3.3.2. Energy structure transition

Currently, fossil fuel accounts for over 70% of global industrial energy demand and great changes in energy structure would be essential to meet the CO2 mitigation requirements.

In the absence of strong incentives or mandatory requirements, changes in the current energy structure would be limited. In all reference scenarios, fossil fuels will continue to be the dominated energy source until mid-century, and their share may even grow slightly and reach 69 – 72% of the gross energy demand in global industry sector by 2050.

With the rapid expansion of India's industry sector, coal's share may continue to increase by a few points to satisfy the growing energy demand. Compared with 2010, the industrial final energy consumption is expected to increase by over two times and over five times respectively by 2030 and 2050. Considering that coal is cheaper than other energy sources, its consumption will experience a sharp increase to satisfy the growing energy demand, and reach over 15 EJ by 2050, four times higher than its 2010 level.

Also benefiting from its cost advantage, coal may remain to be the major energy source in China's industry sector. China's industrial energy demand is expected to peak before 2040, and coal is expected to account for over 40% of the industrial energy consumption until 2050 in most scenarios (see Fig. 6). Only in SSP1 scenario, with the changes towards sustainable development, coal's share may decrease gradually, and reach 21% by mid-century, electricity and natural gas may be used as alternatives during this process.

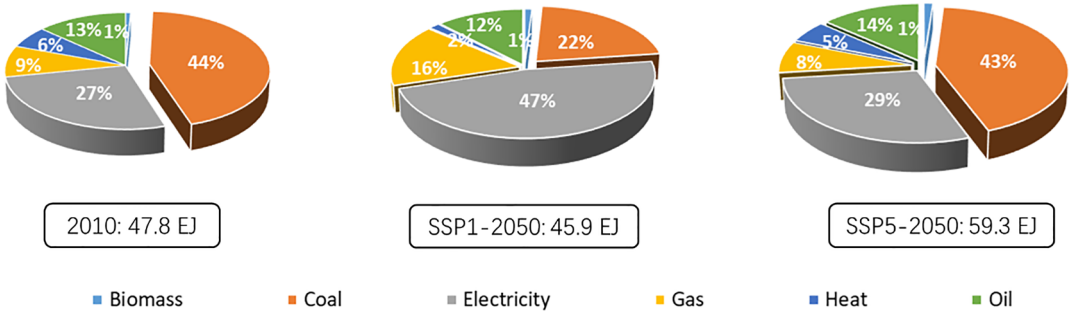

Fig. 6. Final energy structure of China's industry sector in 2010 and in 2050.

In Western Europe, oil and natural gas have already become the major energy resources in industry sector, this structure tends to remain in next decades. Although there might not be significant reductions, the carbon intensity will still be more than 50% lower than China and India by mid-century in reference scenarios, since oil and natural gas are much less carbon-intensive than coal.

When the CO2 emission constraint is introduced to the model, obvious changes in industrial energy structure would be essential, the carbon intensity of global industry sector's energy consumption can be reduced by 34–53% compared with 2010s level through these changes. And to pursue the deep decarbonization in industry sector, regions at different stages of industrialization could face different challenges.

To increase the electrification level is one of the most important measures to reduce direct emissions from industry sector.

In the short term, the electrification progress in industry sector may be rather slow, electricity's share would reach 25% in 2030 from 2010's 21%, during which the continuous improvement in emerging economies is critical. Take India for instance, electricity's share in final energy consumption could rise by 3–9 points from 2015 to 2030, a large scale of electric equipment will be used in newly built factories. However, since the industrial system in Western Europe is already quite complete, and most existing fossil fuel equipment have a technical lifetime of more than 20 years, making new investment for electrical equipment may be not cost-effective, especially when the carbon price is relatively low in this period.

After 2030, rapid electrification will happen in developed regions with the gradual elimination of the old facilities, as a result, most scenarios would have a global average electricity share of over 40% by 2050. In the later stage, developed regions would have a more rapid pace on replacing fossil fuels with electricity, and fossil fuels will only be used for some hard-to-electrified equipment such as steam boiler for the manufacturing industry. For Western Europe, a lot of existing facilities will be phased out at around 2030, and electricity will be widely used in most industries. In SSP5RCP26 scenario, the share of electricity

will increase by around 1 point annually from 2030 to 2050, and reaches nearly 55% by 2050.

Certain processes may not easy to be electrified in industry sector, either for technical obstacles or cost issues, therefore fossil fuels should be consumed in these processes first under 2-degree target. Based on current industrial process flow, it could be very challenging to realize full electrification in industry sector. Take steel industry for instance, a large amount of process heat would be required for its production, changing the heat source from fossil fuels to electricity could greatly increase the cost, and may also reduce the energy efficiency. Besides, coke is an important feedstock for steel production, currently, there are no other alternatives that can be promoted on a large scale. As a result, for the global steel industry, by 2050, 43% of fossil fuels would be used to provide process heat, and another 34% would be used as feedstock, in SSP2RCP26 scenario.

Moreover, the electrification in industry sector would bring extra pressure on power sector. The first challenge is to guarantee enough and stable electricity supply, in most RCP26 scenarios, the electricity demand for global industry sector would be at least 3 times as much as 2010's level, as shown in Fig. 7. Whether this large amount of electricity demand can be satisfied is hard to tell at present, especially for the less developed regions. The second challenge is to promote CO2 mitigation in power sector at the same time, otherwise the electrification process in end-use sectors would become an approach to transfer the CO2 emissions to power sector. Model results show that carbon intensity of power generation is required to decrease to 0.025 tCO2/kWh by 2050 in SSP2RCP26 scenario. In 2010, this indicator was 0.544 tCO2/kWh, indicating a significant amount of renewables and CCS technologies would be required. To face these two challenges, a large amount of R&D investment on new power technologies would be necessary, so as to the active technology communications across regions and early planning on the deployment of advanced technologies.

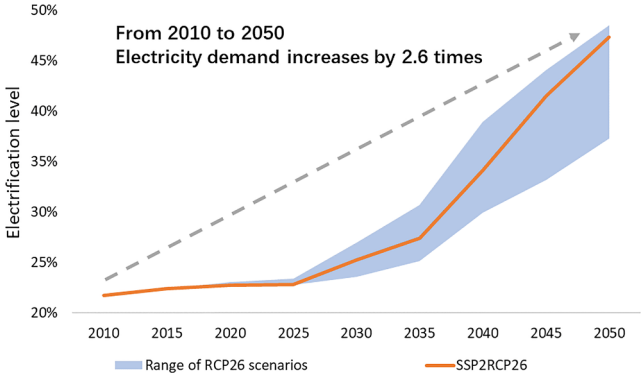

Fig. 7. Electrification level of global industry sector.

Another effective mitigation measure would be the control of coal consumption in industry sector.

In 2010, nearly 40% of CO2 emissions from industrial energy consumption were caused by coal combustion. The rapid reduction of coal combustion is one of the most significant changes from reference scenarios to 2-degree scenarios. In all 2-degree scenarios, coal demand would peak at around 2020, and the peak value is about 36.7–38.5 EJ, 15–20% higher than 2010s level. As shown in Fig. 8, coal demand would decrease with an annual rate of around 2% after 2020, the amount of industrial coal consumption could be reduced to 16.7–18.9 EJ by 2050 in most scenarios. To compare SSP2RCP26 scenario with SSP2 scenario, the reduction of coal could bring nearly 5 Gt of CO2 mitigation.

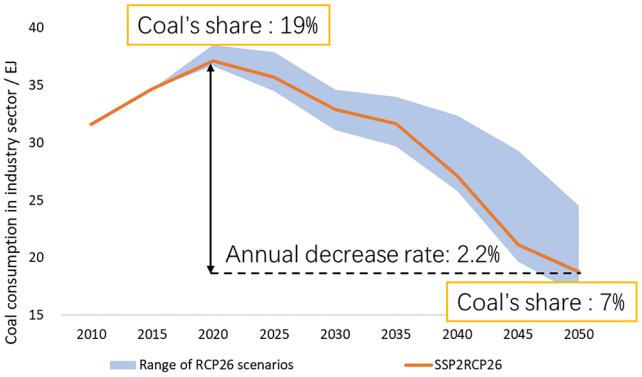

Fig. 8. Coal consumption in global industry sector.

The active participation of industrial enterprises would be the key to reduce the coal consumption, otherwise this goal may become infeasible. Enterprises all over the world are very sensitive to costs, and the cost advantage of coal is the major reason why its consumption keeps to grow in reference scenarios. To weaken this advantage, one effective method would be to build a carbon market to quantify the environment cost of energy consumption. Meanwhile, it is noteworthy that this carbon market should try to cover as many countries as possible, otherwise industry transfer for mitigation cost avoiding may occur.

Under the emission constraint, each region will have to design targeted mitigation strategy for industry sector to meet its unique challenge.

For Western Europe, gas and oil together accounted for around 60% of energy consumption in industry sector at present, this share needs to be significantly reduced. In SSP5RCP26 scenario, gas and oil consumption would reach the peak at 2020, and then begin to slowly decline, the share of gas and oil in total energy demand would be around 57% in 2030. Since 2035, as the existing equipment will be gradually phased out, the consumption of gas and oil is expected to decrease rapidly and only provide 36.8% of the industrial energy consumption by 2050. To reduce oil and gas consumption could be achievable with proper policies, while the sufficient supply of alternative energy could be challenging.

China has a coal-dominated energy structure, the control of coal consumption has already become one of the most important mitigation measures, while the current policy needs to be further enhanced to meet 2-degree target. From model results, in all RCP26 scenarios, coal consumption in industry sector is expected to decrease from now on, and reach 9 EJ level by 2050, which is nearly 60% lower than 2010s level. To meet this requirement, the combination of different measures would be necessary, industrial structure improvement could reduce the energy intensity and the hard-to-electrify demands, the elimination of backward capacities could greatly improve the average energy efficiency, energy management and cascade utilization could reduce the energy waste of whole industry sector.

Oil consumption in India is expected to grow rapidly before 2035, and then be replaced by electricity and gas. To meet the rapidly growing energy demand in industry sector, India's energy structure may experience a unique change, see Fig. 9. Currently, its biggest energy source is coal, while oil may become increasingly important and accounts for around 30% of the total energy demand in 2030, which can temporarily act as the substitution of coal. And with the mitigation task getting more stringent, oil's share would decrease to 18–24% in 2050, and electricity may become the major energy source then in most scenarios.

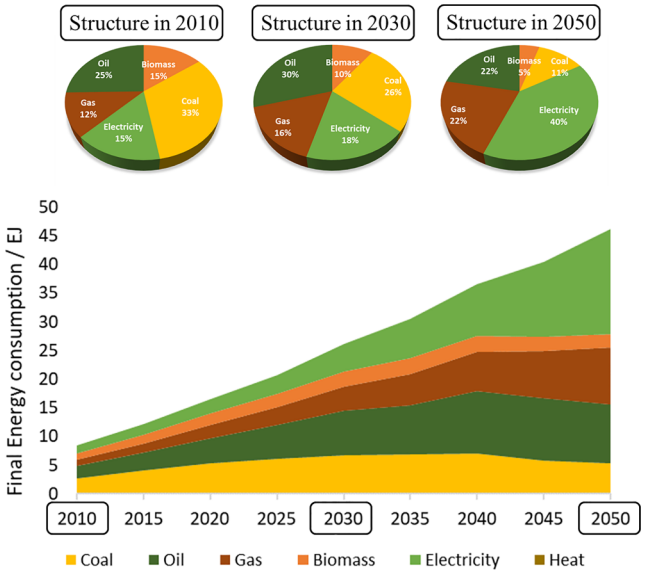

Fig. 9. Final energy consumption and structure of India's industry sector in 2010 and in SSP2RCP26 scenario.

Beyond regional actions, interregional cooperation may also of great significance. Many developed regions including Western Europe have experience on replacing coal with less carbon-intensive fuels such as natural gas, developing regions with coal-dominated energy structure could benefit a lot from their experience on policy support and technology development. Besides, since the technical cooperation could help developing regions to reduce mitigation cost, developed regions may also get an opportunity to make mitigation contributions through carbon trading at a relatively lower price.

4. Conclusions and discussions

Uncertainty in socio-economic trajectory could bring significant impacts to the development of global industry sector. SSP1 (sustainability scenario) would lead to 5.1 Gt of CO2 emission reduction in global industry sector by 2050, compared with SSP5 (fossil-fueled development scenario). However, these transitions are not sufficient to meet the CO2 mitigation requirements of 2-degree target, at least another 6.8 Gt of annual mitigation is required in 2050. From the perspective of carbon budget, a total of 118–173 Gt of cumulative emission reduction should be achieved in global industry sector from 2010 to 2050.

The energy intensity of industry sector may have spontaneous improvements in the coming years, the gap between developed regions and developing regions could be greatly narrowed, especially in RCP26 scenarios. With its economic structure improvement and advanced technologies deployment, China is expected to have the faster reduction speed than the world average, therefore the gap between China and Western Europe could be decreased by over 80% from 2010 to 2050. However, the reductions need to be further accelerated to meet 2-degree target, more measures including stricter energy efficiency standards may be necessary.

Deep decarbonization in industrial energy consumption would be required to achieve the 2-degree target. The increase of electrification rate and the decrease in coal consumption would be the most important changes from the global perspective. In RCP26 scenarios, from 2010 to 2050, electricity consumption in industry sector is expected to increase by 1.2 – 2.9 times, and the coal consumption need to be reduced by 50%.

As the current energy structure varies greatly for different regions, unique features would also occur during the energy structure transition. For post-industrial region Western Europe, as the major energy source is gas and oil, to control the consumption of gas and oil could be one of the most significant measures. In RCP26 scenarios, electricity would provide over 40% of the final energy consumption in Western Europe's industry sector. Therefore, explorations on introducing new energy like solar and geothermal into industry sector would become an urgent task. While for India, which is still at the early stage of industrialization, more fossil fuels may be consumed to satisfy the growing energy demand in the near future, during which process oil and gas may be used to reduce the coal consumption. By 2030, natural gas and oil will become the major energy source and account for nearly 45% of the total final energy consumption. After that, more measures on promoting electrification may become necessary, the electricity demand in industry sector may reach 15,000 PJ by 2050, over three times of 2030's level.

Emerging economies are becoming increasingly important in the global industry sector, and there might be some obstacles for them to promote deep mitigation. Under 2-degree target, India alone may be able to contribute 12–26% of global industrial CO2 mitigation in 2050. Meanwhile, the decarbonization in emerging economies could be more challenging than developed regions. On one hand, access to advanced technologies could be difficult in these regions, to promote energy efficiency improvement would need great effort on both technical progress and policy development; on the other hand, fossil fuels' cost advantage could have greater impacts for enterprises in these regions, especially when they are facing a growing industrial energy demand, specific support on the deployment of low-carbon energy would also be essential. If experience on technical progress and policy development can be shared across developed and developing regions, emerging economies may be able to better tap their mitigation potential.

Most industry enterprises are very concerned about competitiveness, policy design should always take this fact into consideration. For energy intensity improvement, most energy-saving technologies are thought to be no-regret. However, at the beginning, the initial investment on these technologies could be lead to a heavy burden, especially for the small and medium size enterprises. If incentive measures including low-interest loan and subsidy could be implemented, the promotion of energy-saving concept could become easier. For energy structure transition, fossil fuels are more favored by the industrial enterprises mainly for their cost advantage over alternatives. However, it is becoming a consensus that CO2 emission could bring environmental externalities and extra losses, reasonable pricing method of CO2 emission should be necessary to motivate the industrial enterprises to conduct mitigation. One possible approach to price the CO2 emission is to build a free carbon market, but it's also worth noticing that if the carbon market couldn't cover all regions, carbon-intensive industries might be gradually transferred to those regions without carbon market. In this case, industrial enterprises may be able reduce their production cost, while the CO2 mitigation of global industry sector will suffer.

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